

A new method for a local study of nonlinear microwave properties of superconductors

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We report a set of experimental data on local third-harmonic generation at microwave frequencies (0.5 GHz) in $YBa_2Cu_3O_7$ and Nb films. For local investigations of the nonlinear response a probe with inductive coupling was elaborated. The map of the nonlinear microwave response of a $YBa_2Cu_3O_7$ thin film is plotted below T_c with high resolution. The third-harmonic power is measured as a function of temperature, input power and dc magnetic field at some areas of the film. The correlation between the depinning current density J_p and the nonlinear microwave response is also demonstrated.

HTS films find extensive application in passive microwave devices such as transmission lines, antennas and filters¹, owing to a low surface resistance R_s of HTS films, which ensures low losses at low power levels. At higher power surface resistance R_s increases, due to nonlinear properties of these films which leads to higher losses and a shift of the resonance frequency, thus limiting the applicability range for these films. The nonlinearity of surface resistance R_s is generally associated with the Ginzburg-Landau nonlinearity², thermal nonlinearity³, hysteretic losses⁴, and the Josephson nonlinearity⁵. Yet, despite the numerous experiments carried out in this field, the origin of a nonlinear microwave response of superconductor has not been fully understood thus far. Therefore, investigation of nonlinearity is equally important in terms of gaining an insight into the fundamental properties of HTS films and towards applications in superconducting electronics.

In this work we propose a new technique for measuring a nonlinear local microwave response of a superconducting film basing on developed a near-field inductive coupling probe. Using this method, we have plotted a map of the nonlinear local response of a HTS film at a temperature below T_c , and also measured the third-harmonic power as a function of input power, temperature, and applied dc magnetic field for HTS and Nb films.

A wide use in measurements of the nonlinear properties of superconducting films lately has been made of a resonator technique which allows to produce rf magnetic fields that are close in value to the characteristic rf magnetic fields of nonlinearity. This is achieved by using a stripline resonator⁵ or a cavity resonator with a sample placed inside⁶. Characteristic values for the current density or the magnetic field of film nonlinearity are determined either from the power dependence of the third-harmonic power⁷ or from measurements of surface impedance which is related to microwave losses⁵. Note that the averaged nonlinear characteristics of a

microwave device are measured in this case. Local measurements of surface resistance R_s in the microwave range are aided by near-field microscopes in wide use currently. Essentially, the idea of near-field microscopy is in localization of a magnetic or an electric field near probe on scales much less than a wavelength. A variety of probe designs conventionally used for local investigations includes a circular aperture⁸, open-ended coaxial cable⁹, small loop¹⁰, etc.

Here we present an original near-field probe used for measuring a local nonlinear response of superconducting films, that has been designed with due regard for the earlier developed methods and approaches. A block diagram of the probe is shown in Fig.1. The probe is essentially a 2 mm long 50 μ m diameter wire connecting the outer and the inner conductors of a coaxial cable. Reflection of a microwave signal from such a probe gives rise to a high current flow in the wire because the probe impedance is much less than the wave impedance of the coaxial cable. The current induces a fairly strong quasistatic magnetic field localized on a scale of order of the probe diameter. The nonlinear properties of a superconducting film are responsible for generation of higher harmonics which are picked up by the same probe. The incident wave frequency is 472 MHz, and the nonlinear response is measured at the third harmonic frequency of 1.42 GHz. To avoid contact effects preventing observation of a superconducting film nonlinearity, a 10 μ m thick teflon film is placed between the probe and the sample. Note that for the dimensions and the geometry of the probe studied here the maximum of power of about 100 mW produces a maximum current density J_{rf} in the 100 nm film of about $10^6 A/cm^2$.

In this work we did an experimental study of 30-100 nm thick $YBa_2Cu_3O_7$ films magnetron sputtered on a $GaNdO_3$ substrate. The films quality was quite high (critical current density of $\sim 10^6 A/cm^2$). We also investigated Nb films of 30 nm thickness.

Fig.2 shows a temperature dependence of the third-harmonic signal at different levels of input power, which features a nonlinearity peak below T_c . It should be noted that nonlinearity maxima near T_c were observed in a number of works^{2,11}. In¹¹ the nonlinearity peak was shown to appear by penetration of a magnetic flux through the film edges. In our case the probe was placed in a film center, but a sharpest peak remained. For a qualitative analysis of the temperature dependence of nonlinear response, we used the measurements of the temperature dependences of the depinning current density J_p , found from measurements of the residual

magnetization produced in a film by an external uniform magnetic field, the current density of vortex penetration J_c (which corresponds to the Ginzburg-Landau pair-breaking current density J_{GL} for perfect superconductor) and the resistivity ρ , kindly provided by the authors of¹². By comparing these dependences we found out that the temperature of the peak T_{max} , correlates with that at which the depinning current density J_p disappears, and the temperature of nonlinearity vanishing corresponds to the off-set temperature $\rho(T)$. The correlation between the nonlinear microwave properties and the depinning current density indicates that the nonlinearity observed at temperatures close to T_c is of a vortex origin.

In Fig.3 the third-harmonic power $P_{3\omega}(P_\omega)$ is shown as a function of input power on a log-log scale for $YBa_2Cu_3O_7$ and Nb films. The data are readily approximated by the power law $P_{3\omega} \sim AP_\omega^n$. At temperatures close to T_c the HTS films exhibit a deviation from the exponent $n = 3$ (which is characteristic of an ordinary cubic nonlinearity described by the Ginzburg-Landau equations), while Nb films feature a marked power threshold. The exponent deviation from $n = 3$ for HTS films occurs through saturation of the power dependence of the third-harmonic signal at high input powers or at temperatures close to T_c ¹¹.

The third-harmonic power $P_{3\omega}(H_{dc})$ as a function of a dc magnetic field H_{dc} at a temperature near the nonlinearity peak and at $T = 77$ K is shown in Fig.4. The behavior of $P_{3\omega}(H_{dc})$ differs qualitatively at liquid nitrogen temperature and temperatures close to T_c . At $T = 77$ K there is a rise in the third-harmonic value and a fairly strong hysteresis is observed, whereas in the vicinity of T_c irreversibility disappears and an increase in the field causes suppression of nonlinearity. A strong dependence on an external magnetic field is also evidence of the vortex origin of the observed nonlinearity; it may be connected with a decrease in the depinning current density J_p at higher temperatures (Fig.2).

The method developed was used to map a nonlinear local microwave response for $YBa_2Cu_3O_7$ at liquid nitrogen temperature, as shown in Fig.5. We have chosen a positioning system such that it would allow the probe to be moved at a $125 \mu m$ step in the direction of the x and y axes. Fig.5 demonstrates a nonuniform distribution of the nonlinear response across the film surface, which depends on the inhomogeneity of the critical current density in the sample. Note also that nonlinearity increases in areas lying closer to the sample edge, when the probe is parallel to the film boundary. This effect can be explained by an increasing density of the current excited in the film.

Although a complete quantitative analysis of the experimental data is impossible currently, some qualitative considerations seem plausible enough. Estimated value of the highest current density $J_{rf} \sim 10^5 - 10^6 A/cm^2$ in the film is higher or of the order of the current density of vortex

penetration J_c and it is naturally to consider that the nonlinear response is due to creation of vortices by microwave field. At the same time the relation between the temperature dependences of the nonlinearity and the depinning current density J_p (Fig.2), and disappearance of irreversibility in the dc magnetic field dependence of the third-harmonic power (Fig.4) demonstrate the substantial role of thermal fluctuations in the vortex response. The nonlinear response of low-temperature superconductors, unlike in the HTS case, demonstrates a power threshold likely to be related to the onset of vortex creation by the microwave field.

In summary, a new method for local investigation of the nonlinear microwave properties of superconducting films has been developed and used for mapping of a nonlinear response from a HTS film at liquid nitrogen temperature. The third-harmonic power was measured as a function of temperature, input power and external dc magnetic field for superconducting films. It argues that the origin of the observed nonlinear response is likely due to creation of vortices in the film by the microwave field or an external dc magnetic field.

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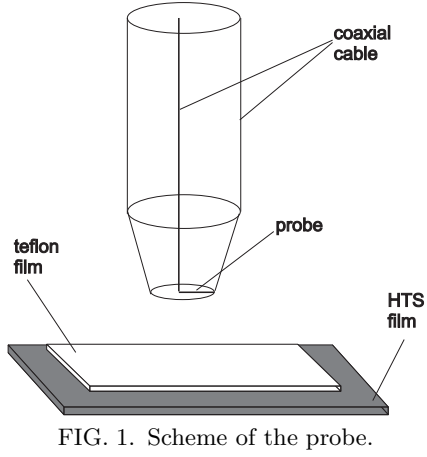


FIG. 1. Scheme of the probe.

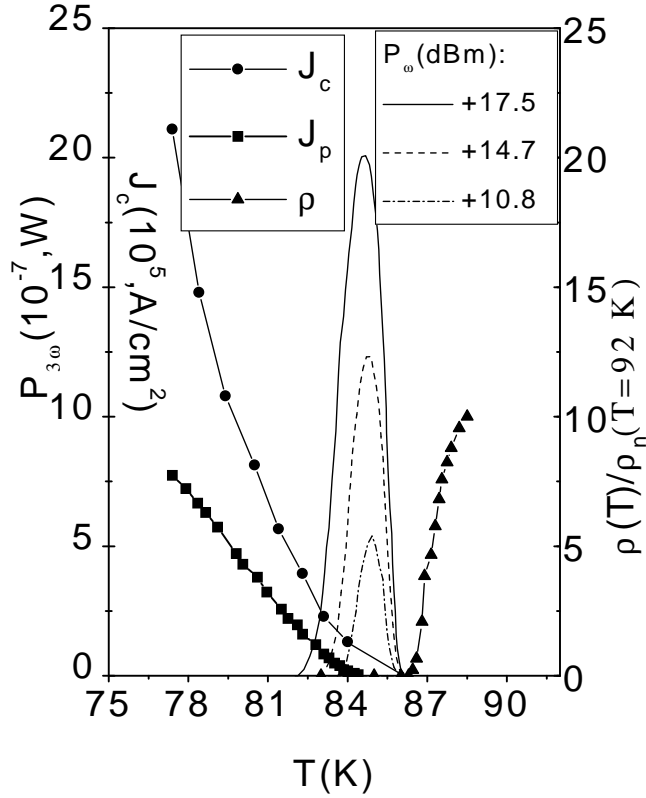


FIG. 2. Temperature dependences of the third-harmonic signal $P_{3\omega}(P_\omega)$ at various input powers, depinning current density J_p (squares), current density of vortex penetration J_c (circles) and resistivity ρ (triangles) for $YBa_2Cu_3O_7$ film.

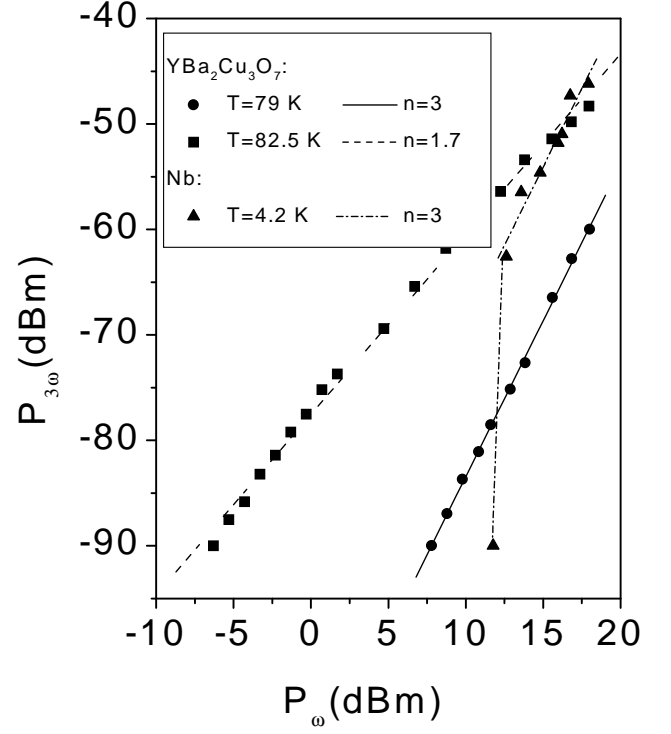


FIG. 3. $P_{3\omega}$ vs P_ω for $YBa_2Cu_3O_7$ film at temperature near the peak $T = 82.5$ K (squares), $T=77$ K (circles) and Nb film at $T= 4.2$ K (triangles), fitted by the power-law $P_{3\omega} \sim AP_\omega^n$ shown by straight lines.

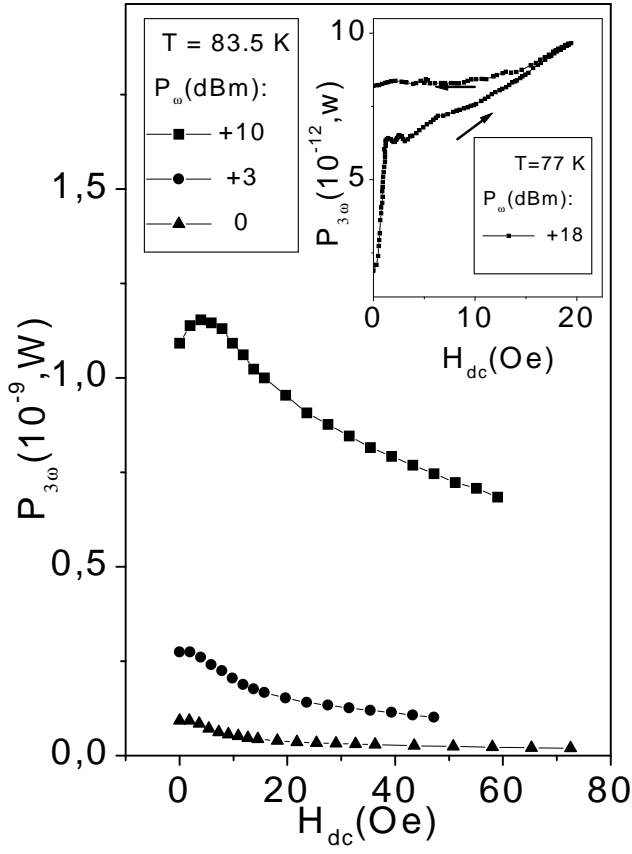


FIG. 4. $P_{3\omega}$ vs H_{dc} at different levels of input power at temperature near the peak of nonlinearity $T = 83.5$ K for $YBa_2Cu_3O_7$ film. The inset shows $P_{3\omega}(H_{dc})$ at temperature $T = 77$ K for $YBa_2Cu_3O_7$ film.

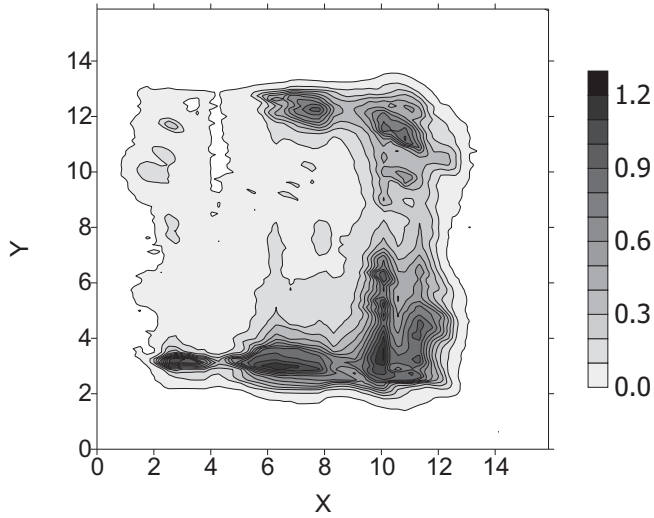


FIG. 5. The map of the nonlinear response of $YBa_2Cu_3O_7$ film at $T = 77$ K. Sizes of image is shown in mm. The probe is parallel to the x axis.